Design Flood Estimation Using a Continuous Simulation Modeling Approach

JC Smithers and KT Chetty

School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal
Email: smithers@ukzn.ac.za

Abstract

The estimation of design floods is necessary for the design of hydraulic structures. Many of the limitations of an event-based approach to design flood estimation, such as the estimation of antecedent soil moisture conditions and the assumption that the exceedance probability of the design flood is the same as the exceedance probability of the design rainfall, may be overcome by the use continuous simulation modelling. The development of a continuous modeling system for design flood estimation in South Africa has focused on the required scale of application and levels of soils and land cover information, the development and evaluation of a method to disaggregate daily rainfall into hourly totals, the assessment of a methodology to improve the estimation of catchment rainfall and the development and assessment of techniques for flood routing in ungauged catchments. Progress and results from these components of the study are reported in this paper.

Keywords: *design flood estimation, continuous simulation modeling, spatial rainfall*

1 Introduction

Recent floods such as those in February 2000 which occurred in the North-Eastern part of South Africa, Zimbabwe and Mozambique and flooding in the Western Cape in 2005 highlight the need to assess the risks associated with floods. Design flood estimation, where the magnitude of a flood is associated with a level of risk (e.g. return period) is necessary in the design of hydraulic structures (e.g. bridges, culverts, dam spillways, drainage canals etc).

Reliable estimates of flood frequency in terms of peak flows and volumes remain a challenge in hydrology (Cameron *et al.*, 1999). Cordery and Pilgrim (2000) express the opinion that the demands for improved estimates of floods have not been met with any increased understanding of the fundamental hydrological processes. The urgency for new approaches to design flood estimation in South Africa is highlighted by, Alexander (2002) and Smithers and Schulze (2003).

Standard techniques for flood estimation have been developed for most countries and procedures for design flood estimation may be broadly categorised as methods based on the analysis of observed floods and rainfall based methods. The situation which faces design engineers and hydrologists most frequently is when no, or inadequate, observed streamflow data are available at the site of interest and then either regional approaches or rainfall-runoff models have to be used for design flood estimation. Reviews of approaches to design flood estimation are contained in Cordery and Pilgrim (2000), Smithers and Schulze (2001) and Gorgens (2002).

Rainfall data are far more abundant and have longer records than streamflow in South Africa. Hence, event-based approaches such as the Unit-Hydrograph, Rational Method and SCS methods, which are generally simple to apply and which lump complex, heterogeneous catchment processes into a single process or index, are currently widely used for design flood estimation in South Africa. A major limitation of event-based methods is the assumption that the exeedance probability of the simulated streamflow is the same as that of the input design rainfall. Many studies have shown that this is generally not the case and that the antecedent soil moisture conditions prior to an event are significant in determining the runoff response (Schulze and Arnold, 1979; Schulze, 1982; Schmidt and Schulze, 1984; Dunsmore *et al.*, 1986; Pilgrim and Cordery, 1993). Another major limitation of event-based methods is the inability of most of the methods to account for antecedent soil moisture conditions prior to flood events, which may result in unrealistic estimates of runoff. Event-based models utilise a single estimate of design rainfall to estimate the design flood over a catchment. Recent experiences in South Africa suggest that multi-catchment storms have been responsible for floods which have caused large scale destruction and loss of life.

The limitations of event-based approaches to design flood estimation can be overcome by adopting a continuous simulation approach to rainfall-runoff modelling. Frequently in practice the entire design hydrograph, and not only the peak discharge, is required when designing, for example, flood reducing detention ponds and emergency spillways for dams. The output from a continuous simulation approach, which can include the entire hydrograph, can be analysed directly, and hence the exceedance probability of the flood is not dependent on the exceedance probability of the input rainfall. Current or predicted patterns of rainfall and land use in the catchment may be modelled explicitly. Runoff from varying rainfall over multiple catchments can also be simulated and analysed.

Antecedent soil moisture conditions are modelled explicitly and hence realistic runoff responses to rainfall events can be obtained. An additional advantage of the continuous simulation modelling approach is that the flood attenuating effects of, for example, river reaches and dams can be directly accounted for by the model. These and other advantages of continuous simulation modelling for design flood estimation are reported in the international literature (e.g.Boughton and Hill, 1997; Rahman *et al.*, 1998; Cameron *et al.*, 1999; Reed, 1999) and continuous simulation modelling has been used for design flood estimation in a number of international studies (Calver and Lamb, 1995; Boughton and Hill, 1997; Calver *et al.*, 1999; Cameron *et al.*, 1999; Lamb, 1999; Steel *et al.*, 1999; Calver *et al.*, 2000; Calver *et al.*, 2001; Calver *et al.*, 2004) and has also been demonstrated in South Africa (Smithers *et al.*, 1997; Smithers *et al.*, 2001). According to Rahman *et al.* (1998) some of the disadvantages of CSM include the loss of "sharp" events if the modelling time scale is too large, the extensive data requirements, which result in significant time and effort to obtain and prepare the input data, and the expertise required to determine parameter values such that historical hydrographs are adequately simulated. Despite these disadvantages, CSM may prove to be the most powerful means of estimating flood frequency from rainfall (Rahman *et al.*, 1998) and CSM for design flood estimation is receiving increasing interest and use in the USA (ASCE, 1997). Calver *et al*. (2000) express the opinion that CSM may form the basis for the next generation of flood frequency estimation in the UK.

The Water Research Commission is currently funding a project titled "The development of a continuous simulation modelling system for design flood estimation in South Africa". In this project the following aspects are being investigated:

- The scale of application and levels of soils and land cover information necessary to apply continuous simulation modelling for design flood estimation.
- The development and evaluation of a method to disaggregate daily rainfall into hourly totals in South Africa.
- An assessment of merged raingauge and radar data to estimate the spatial distribution of rainfall in the Liebensbergvlei catchment and the use of improved estimates of catchment rainfall for modelling. In addition, an initial assessment of the stochastic, fine resolution, space-time String-of-Beads model to simulate catchment rainfall has been performed.
- The development and assessment of techniques for flood routing in ungauged catchments.

The objective of this paper is to report on progress made towards developing a continuous simulation modelling system for design flood estimation in South Africa and will focus on the progress made with respect to the above four aspects of the project.

2 Model Selection and Catchment Configuration

The model selected for the development of the CSM system is the *ACRU* model (Schulze, 1995). Two previous studies on continuous simulation modeling for design flood estimation in South Africa reported by Smithers *et al* (1997) and Smithers *et al*. (2001) also made use of the *ACRU* model with reasonable results. The *ACRU* model is a physical-conceptual agrohydrological model which operates on a daily time step. The model simulates all major processes of the hydrological cycle which affect the soil water budget and is capable of simulating, *inter alia*, streamflow volume, peak discharge and hydrograph, reservoir yield, sediment yield, crop yield for selected crops and irrigation supply and demand. *ACRU* can operate at a point, as a lumped catchment model, or as a distributed cell-type model in order to account for spatial variability in climate, land use and soils.

The study area selected to evaluate the CSM system is the Thukela catchment located as shown in Figure 1, which extends latitudinally from 27^{o} 25' to 29 ^{o} 24' S and longitudinally from 28 ^{o} 58' to 31 ^{o} 26' E and covers an area of approximately 29000 km^{2} in the KwaZulu-Natal province of South Africa. The Thukela river has its source in the Drakensberg mountain and flows right through into the Indian Ocean. The mean annual precipitation (MAP) in the Thukela catchment ranges from approximately 2000 mm in the Drakensberg to as low as 550 mm in the drier central regions and most of the rainfall is received during the mid-summer months from December to February. The Thukela catchment comprises of 86 quaternary sub-catchments which have been further delineated into 235 sub-catchments for modelling purposes.

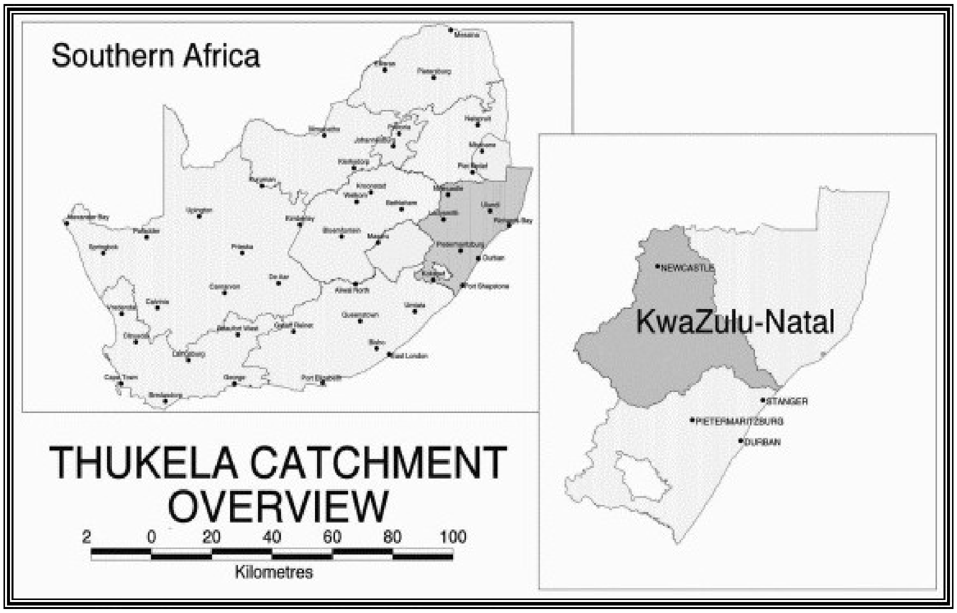

Figure 1. The Thukela Catchment

The development of the CSM system comprises of investigations into and refinements of different components which include the spatial scale and levels of soils and land cover appropriate for CSM, spatial and temporal distribution of rainfall, rainfall disaggregation and routing floods in ungauged catchments. The methods and results of these refinements are detailed below.

3 Scale and Levels of Soil and Land Cover Information

The spatial resolution at which continuous simulation modeling is to be implemented in South Africa is important in order to obtain realistic design estimates. It is therefore necessary to investigate the appropriate range of scales at which the CSM system should be applied. Soil and land cover information also play an important role in CSM as they influence the hydrological response of a catchment. The objective of this component of the study is to investigate the appropriate scale at which CSM should be implemented and the levels of soil and land cover information required to give optimum simulation results i.e. to investigate the optimal catchment discretisation for CSM with the *ACRU* model, using readily available soils and land cover information.

The research strategy adopted was to select a limited number of catchments with a range of catchment areas and model each of the selected catchments to investigate the optimum scale for catchment discretisation. The methodology also included modeling the selected catchments with different levels of soils and land cover information i.e. using area weighted and modal values to represent catchment soils and land cover information in the model. The Thukela catchment, as shown in Figure 1, was selected for the investigations. Five catchments with areas ranging from 155 km^2 to 820 km^2 were selected from the 86 quaternary catchments in the Thukela catchment for this component of the investigation (Figure 2). The catchments were selected based on the size of the catchment and the availability of rainfall and observed runoff data

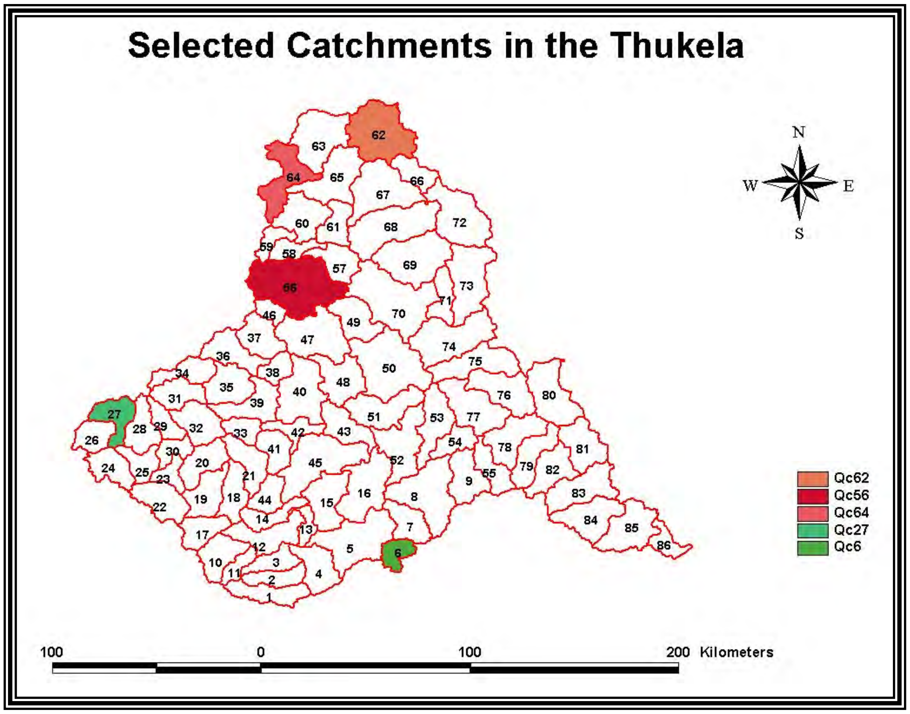

Figure 2. Selected catchments in the Thukela catchment

Soils information was obtained from the ISCW soils maps (SIRI, 1987) at a 1: 50 000 scale which has been translated into *ACRU* variables using a methodology developed by Pike and Schulze (1995). Land cover information was obtained from the National Land Cover Database (CSIR, 1999) at a resolution of 1: 250 000 and has been translated into *ACRU* variables by Schulze (2001). For the purpose of this investigation, both area weighted and modal soils information were obtained for the catchments, both at quaternary and sub-quaternary scales.

In order to compare the effects of soil and land cover information at different spatial scales on runoff depths, a number of scenarios were simulated for each of the selected catchments, as shown in Table 1. The catchments were modelled as a single entity, then as sub-catchments and finally as hydrological response units (HRU) where each HRU represents a dominant land cover class. The period of simulation was from 1950 to 2000.

Table 1. Scenarios simulated for different soils and land cover information for each of the selected catchments

Scenario	Soils Information	Land Cover Information	Sub-catchments / HRU's
1 (lumped)	Area weighted for whole QC	Modal for whole catchment	Lumped
2 (modaws)	Area weighted per sub-catchment	Modal per sub-catchment	Sub-catchments
3 (hruaws)	Area weighted per sub-catchment	Catchment specific	Hydrological response units
4 (hrumod)	Modal per sub-catchment	Catchment specific	Hydrological response units

For Scenario 1 the catchment was modeled as a single entity (lumped) and area weighted soils information was used. The modal land cover class i.e. cover class with the highest percentage area in the catchment, was used. For Scenarios 2 the quaternary catchment was divided into sub-catchments according to topography. For Scenarios 3 and 4, the sub-catchments were modeled as HRUs. Four dominant land cover classes were identified for each sub-catchment and therefore each sub-catchment was modeled with four HRUs. Area weighted soils information was used in Scenario 3 and modal soils information for each HRU in Scenario 4 was simulated.

Figure 3 conmtains the 50th percentile of non-exceedence for observed and simulated monthly streamflow depths in QC 6 for the four scenarios. From Figure 3 it is evident that the simulated streamflow follow the rainfall pattern more closely than the observed streamflow and this could be attributed to irrigation practices taking place in the catchment, which have not been incorporated into the modelling exercise. It is also evident that there are differences between the scenarios modelled. In this particular catchment, there is less streamflow simulated from a lumped catchment during the summer/rainy season than the streamflow simulated from the delineated sub-catchments. Comparison between scenarios indicate that when using area weighted values to derive sub-catchment soil and land cover information results in more simulated runoff compared to when modal values are used. Similarly, further division of the sub-catchments into HRU's and using area weighted soils and land cover results in different simulated streamflow. It is important to note that the results obtained from simulations in QC6 highlight the complexities of modelling at different scales in operational catchments. These results shown here are typical for QC 6 and further analyses will be performed on the other selected catchments which have a range of catchment areas and the simulations will include peak discharge estimation.

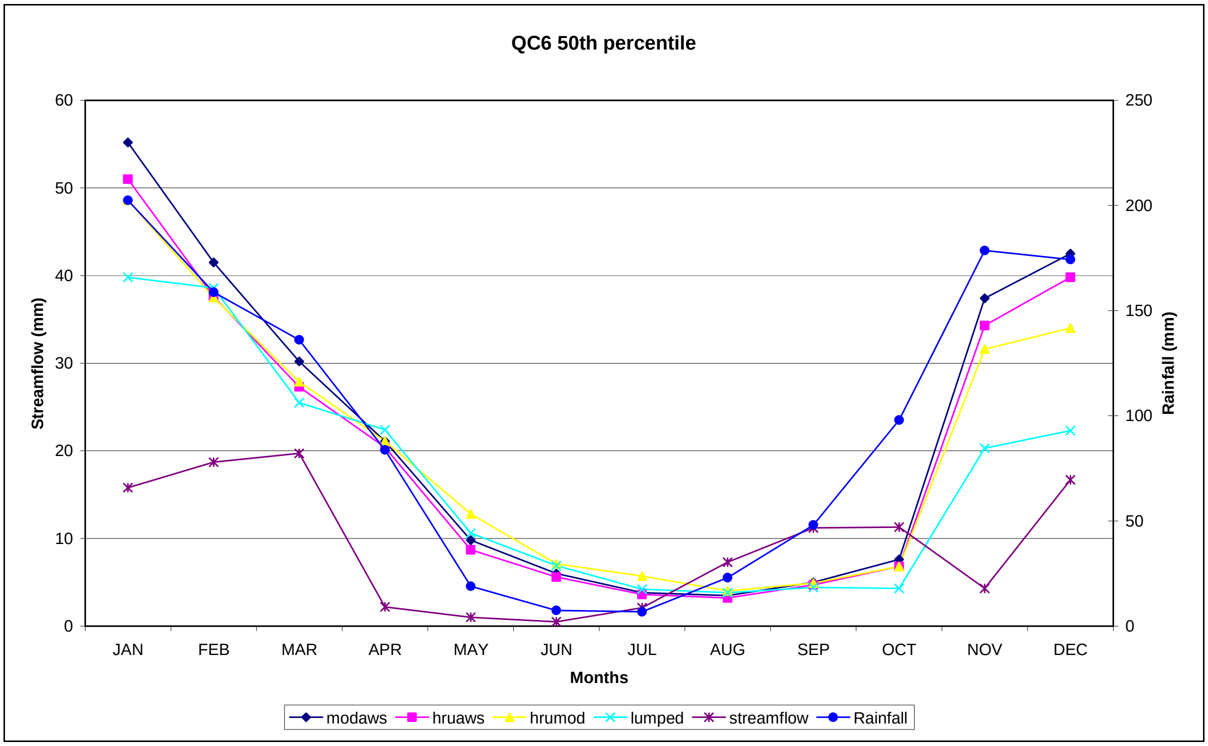

Figure 3. Comparison of the 50th percentile of non-exceedence in QC6 for the different scenarios listed in Table 1

4 Disaggregation of Daily Rainfall

In order to generate a hydrograph from the daily volume of runoff simulated by the *ACRU* model, it is necessary to dissagregate the input daily rainfall into shorter time increments. Currently the model utilises four regionalised synthetic rainfall distributions, which were developed from design rainfall information (Weddepohl, 1988), to disaggregate the daily rainfall.

The methodology adopted, refined and regionalised by Knoesen (2005) for South Africa is based on a model developed by Boughton (2000), which disaggregates daily rainfall to hourly rainfall values, while retaining the daily total and the statistical characteristics of the hourly rainfall at the gauge site. The primary part of the model is the distribution of the fraction, R, which is the fraction of the daily total that occurs in the hour of maximum rainfall. Two examples of the distribution of R are shown in Figure 4 for sites in differing climates. Jonkershoek (Station Jnk19a), in the Western Cape, is located in a winter rainfall region whereas Ntabamhlope (Station N23) in the KZN midlands, is located in a summer rainfall region.

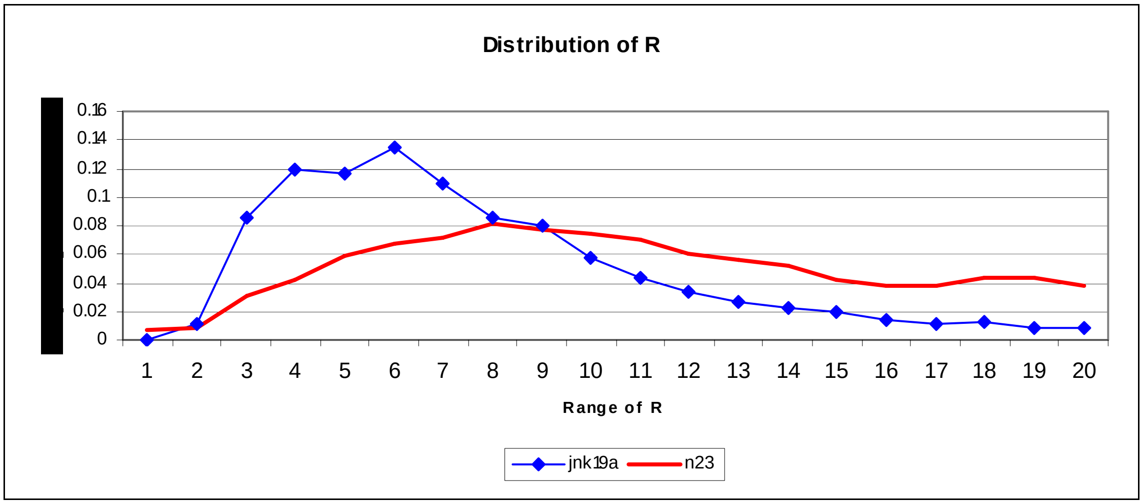

Figure 4. Frequency distributions of R at Jonkershoek (Jnk19a) and Ntabamhlope (N23) (Knoesen, 2005)

A random number is used to sample from the distribution of R for a given average R. The sample value of R determines the other 23 hourly values, which then undergo a clustering procedure, together with the value for R, in order to best maintain the observed statistics for 2, 3, 6 and 12 hour rainfall durations. This clustered sequence can then be arranged into 1 of 24 possible temporal arrangements, depending on when the hour of maximum rainfall occurs. The structure of the model allows for the production of 480 different temporal distributions.

The model can utilise at-site short duration rainfall, if available, or can use regionalised information to disaggregate daily rainfall into hourly values at any location in South Africa. An example of the performance of a regionalised application of the model at Ottosdal in the North-West Province is shown Figure 5, which include the statistics computed from the observed data and the inter-quartile statistics of 100 disaggregated rainfall series.

As documented by Knoesen (2005), the performance of the disaggregation model was analysed firstly by comparing moments and event characteristics computed for the observed data and disaggregated series, and secondly by comparing design rainfall values computed from the observed data and disaggregated series. From the results obtained by Knoesen (2005) at 15 independent test sites located in differing climatic regions of South Africa it is evident that, particularly when short duration data are available, the disaggregation model is able to produce short duration rainfall where the mean, standard deviation and skewness are very similar to that of the observed data. However, the statistics and event characteristics related to the structure of the rainfall are not simulated as well, and it postulated that this is the result of the methodology used to sequence the disaggregated hourly rainfall values. Furthermore, Knoesen (2005) postulates that the use of different distributions to represent rainfalls of different magnitude ranges will improve the simulation of dry probabilities and design rainfall depths. Knoesen (2005) concludes that that the model can be used to reasonably disaggregate daily rainfall at locations where no short duration data are available. The disaggregation model will be incorporated into the CSM system to improve the generation of hydrographs by the CSM system.

5 Flood Routing in Ungauged Catchments

When modelling large catchments with the *ACRU* model, catchments are generally subdivided into sub-catchments, each with its own rainfall and catchment characteristics. Runoff from each sub-catchment is routed through downstream river reaches to the catchment outlet. The Muskingum method of flow routing in river reaches is used in *ACRU* (Smithers and Caldecott, 1993). However, without observed flow data, the Muskingum K and X parameters are difficult to estimate. The objective of this component of the study, undertaken by Tewolde (2005), was to assess Muskingum-based methods for flow routing in ungauged river reaches, both with and without lateral inflows. Three sub-catchments in the Thukela catchment were selected for analyses, with river lengths of 4, 21 and 54 km. The location of the gauging weirs is shown in Figure 6.

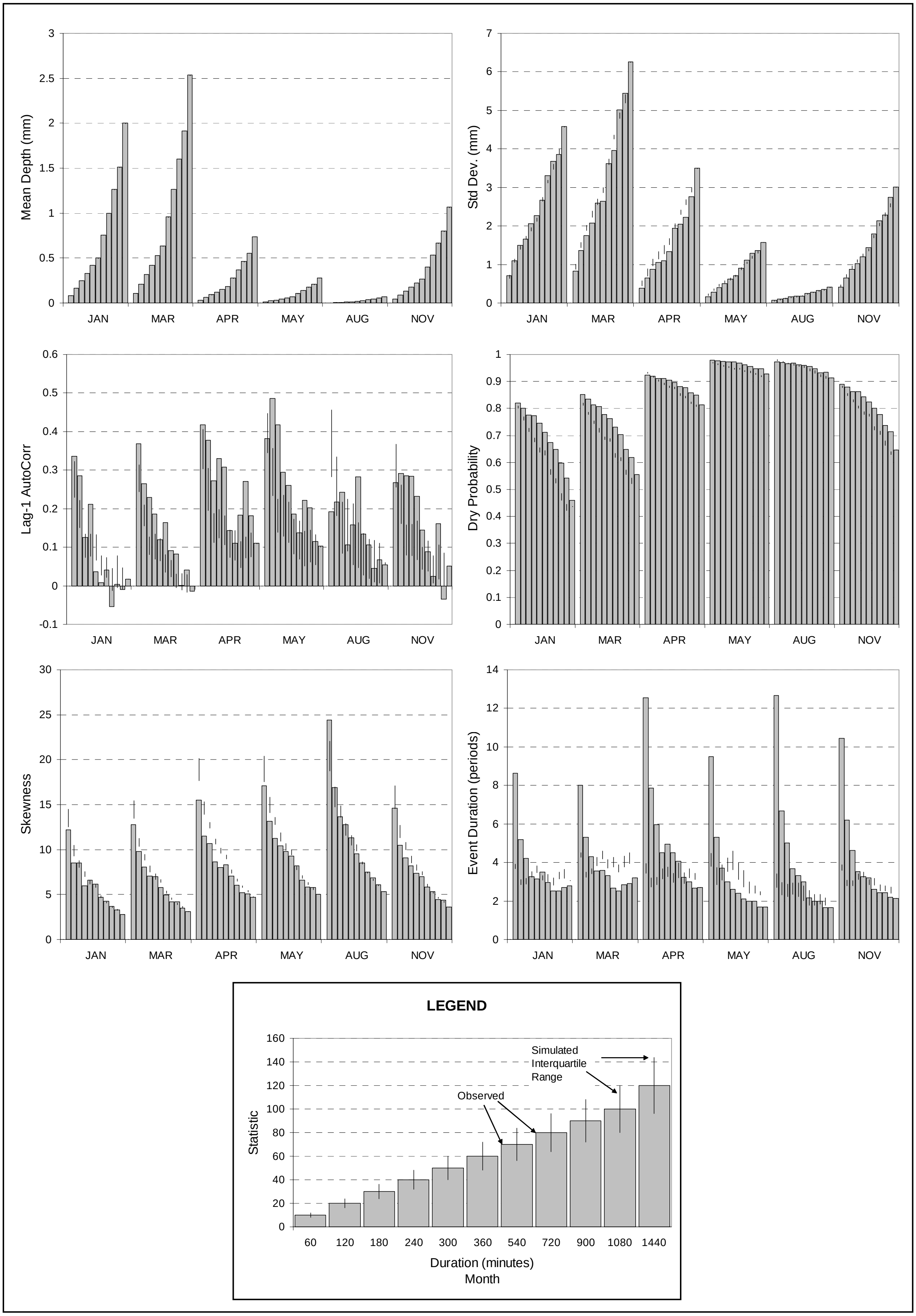

Figure 5. Simulated performance of the rainfall disaggregation model at Station 0435019 (Ottosdal, North-West province), when regionalised input is used (Knoesen, 2005)

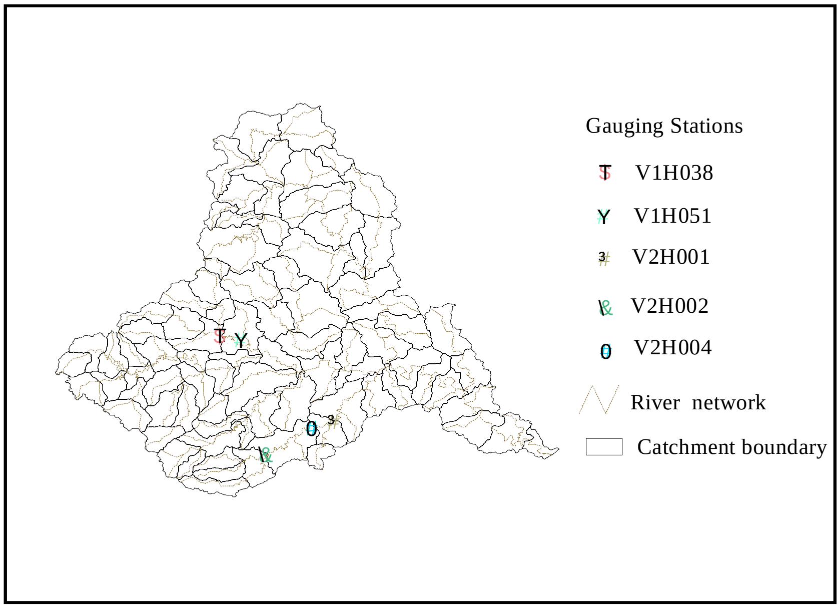

Figure 6. Selected gauging stations in the Thukela catchment

Using observed data, the Muskingum parameters were calibrated by Tewolde (2005) to assess the performance of the Muskingum flood routing method. For application in ungauged catchments, Tewolde (2005) derived the Muskingum parameters using the Muskingum-Cunge metholodogy (Cunge, 1969) and used two approaches to estimate the depth:discharge relationships for the reaches. The first method (MC-E) utilised an empirical relationship between the wetted perimeter and discharge, reported by Punmia and Pande (1981), and the second approach (MC-X) estimated the depth:discharge relationship from assumed river cross-sections using the methodology described by Smithers and Caldecott (1995). An example of routing an event from Gauging Weir V2H002 to V2H004 (Figure 6) for a reach length of 54.4 km, is shown in Figure 7.

The results obtained by Tewolde (2005) show that the computed outflow hydrographs generated using the Muskingum-Cunge method, both with the empirically estimated variables and variables estimated from cross-sections of the selected rivers, resulted in reasonably accurate computed outflow hydrographs with respect to peak discharge, timing of peak flow and volume. This led Tewolde (2005) to conclude that the Muskingum-Cunge method can be applied to route floods in ungauged catchments in the Thukela catchment and it is postulated that the method can be used to route floods in other ungauged rivers in South Africa.

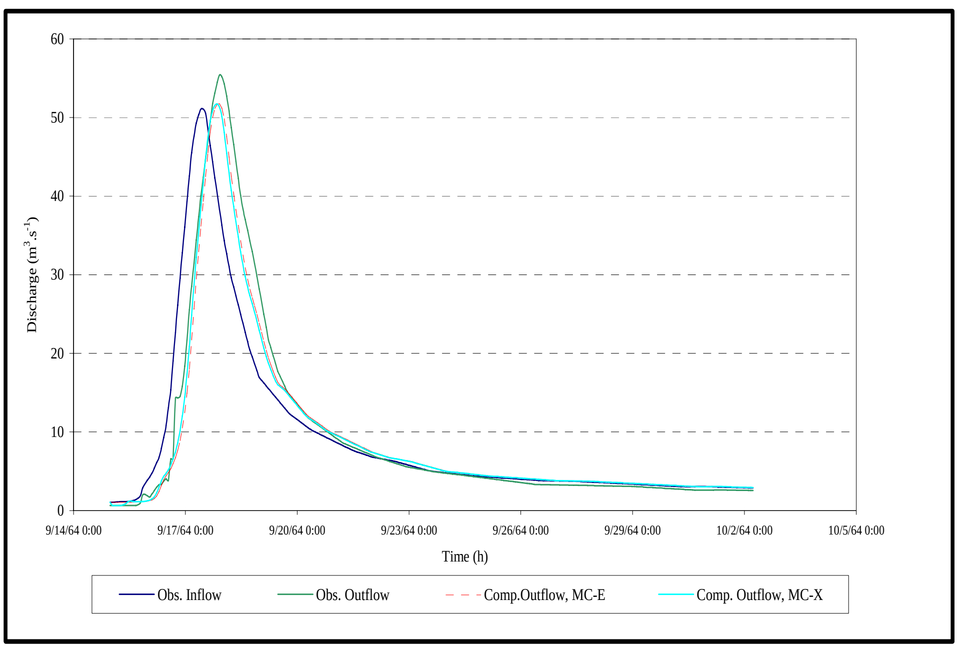

Figure 7. Observed and computed hydrographs at Gauging Weir V2H004 (Tewolde, 2005)

6 Improved Estimation of Rainfall over a Catchment

Assuming a uniform distribution of rainfall over a catchment may result in significant errors in the simulated runoff. A number of techniques have been developed to improve the estimation of the spatial distribution of rainfall from sparsely distributed raingauges. These techniques range from simple interpolation techniques developed to estimate areal rainfall from point rainfall measurements, to statistical and deterministic models, which generate rainfall values and downscale the rainfall values based on the physical properties of the clouds or rain cells. Furthermore, these techniques include different statistical methods, which combine the rainfall information gathered from radar, raingauges and satellites. Although merging the radar and raingauge rainfall fields gives the best estimate of the "true rainfall field", the length of radar records and the spatial coverage of the radar in a country such as South Africa is relatively short and hence is of limited use in hydrological studies. The objectives of this component of the project were to:

(i) Develop and assess a methodology to improve the estimation of the average depth and spatial distribution of rainfall over a catchment, using radar images and point rainfall data.
(ii) Assess the influence of the improved catchment rainfall on simulated streamflow.
(iii) Evaluate a detailed space-time stochastic rainfall model to generate long sequences of rainfall over a catchment for use in a continuous simulation model.

Frezghi (2005) used an algorithm to merge radar and raingauge data developed by Sinclair (2004), which is based on the conditional merging technique proposed by Ehret (2002). Both tipping bucket and daily raingauges in the Liebensbergvlei catchment and radar images from the radar located near Bethlehem were used by Frezghi (2005) to validate and verify the merging algorithm. The validations performed by Frezghi (2005) indicate that the merging procedure correctly retained the gauged rainfall values used to condition the radar derived rainfall after areas masked as having zero rainfall because the radar reported no rainfall, even though raingauges may have reported rainfall in the area, were removed from the analysis.

Frezghi (2005) also verified the merging process by comparing the merged rainfall values with gauged rainfall at the locations of daily raingauges not used in the merging process. An example of the independent verification of the merging process is shown in Figure 8.

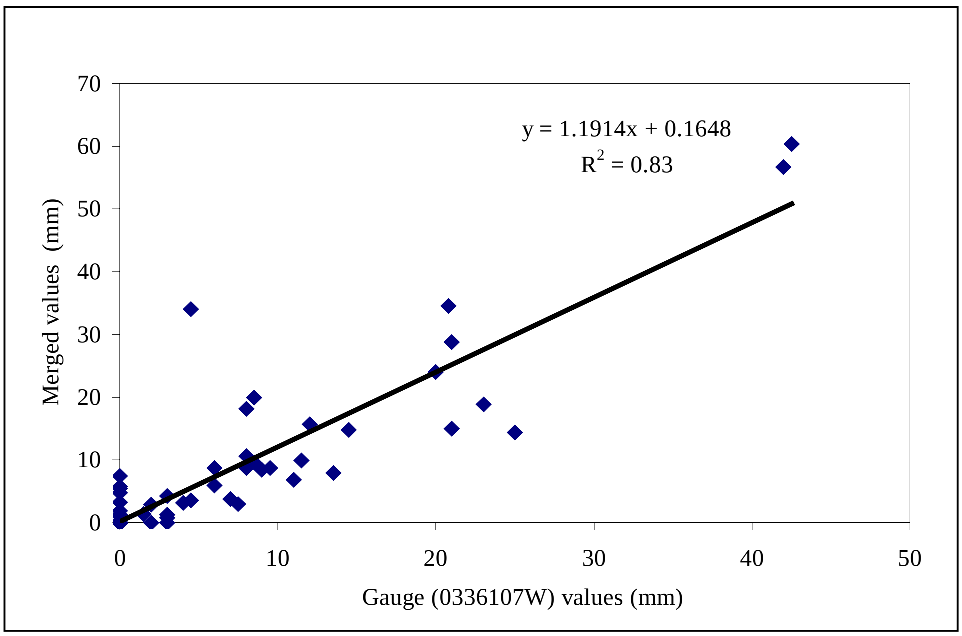

Figure 8. Comparison of daily rainfall from Raingauge 03312607W, which was not used in the conditioning of radar rainfall values, and merged pixel rainfall values at the raingauge location, after merged zero rainfall values resulting from no rainfall in the radar images were removed (Frezghi, 2005)

Regression relationships were also developed between the average merged rainfall depths for a particular catchment and a raingauge selected to represent the rainfall in the subcatchment, for example as shown in Figure 9. These relationships were derived for the period when both radar and gauged rainfall data were available and could be used to improve the estimation of sub-catchment rainfall for the remainder of the historical daily rainfall record. Frezghi (2005) also noted that raingauges generally overestimate the rainfall falling in a sub-catchment, as shown in Figure 9. These results highlight both the potential errors in estimating rainfall for a catchment using a raingauge and the need to use the merging process, where radar data are available, to estimate catchment rainfall. Frezghi (2005) utilised the improved estimates of sub-catchment rainfall to show that the *ACRU* model generated significantly less runoff (approximately 30% less in the Liebenerbergvlei catchment) using the merged estimates compared to the conventional, adjusted "driver" rainfall station approach.

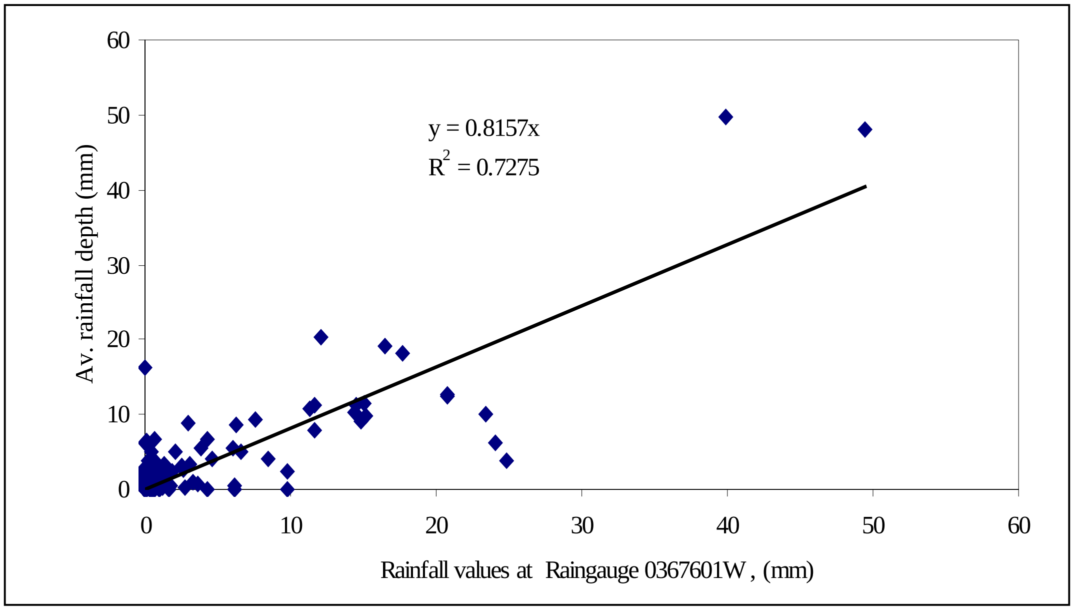

Figure 9. Average daily sub-catchment rainfall derived from the merged rainfall field vs rainfall from Raingauge 037601W in Subcatchment 26 (827.34 km^2) (Frezghi, 2005)

The String of Beads Model (SBM) developed by Pegram and Clothier (2001a; 2001b) was used by Frezghi (2005) to generate synthetic rainfall series for the Liebenbergsvlei catchments. The SBM model is able to produce rainfall values at a spatial resolution of 1x1 km with a 5 minute temporal resolution. The SBM is a high-resolution space-time model of radar rainfall images, which takes advantage of the detailed spatial and temporal information captured by weather radar and combines it with the long-term seasonal variation captured by a network of daily raingauges. Statistics from a 50 year period of generated rainfall values were compared by Frezghi (2005) with the statistics computed from a 50 year raingauge data series, and it was found that the generated rainfall values mimic the rainfall data from the raingauges reasonably well.

7 Discussion and Conclusions

Improvement to components of the CSM system have been made. The investigation to date into the scale and levels of soil and land cover information necessary for adequate CSM indicate that modeling at quaternary catchment scale is too large and that further sub-catchment delineation is required in the Thukela catchment. The methodology developed for the disaggregation of daily into hourly rainfall has been shown to be successful at ungauged sites and will introduce a stochastic element to the CSM system. The use of the Muskingum-Cunge method for flood routing in ungauged river reaches, using either the empirical or typical cross-section method to estimate the depth:discharge relationship for the reach, will enable the CSM system to be applied in ungauged catchments. The merging of radar and raingauge data in the Liebensbergvlei catchment has shown the merging process to adequately represent the spatial distribution of rainfall in a catchment and that the methodology used to relate merged catchment rainfall to gauged rainfall data should be applied, where possible, to improve the estimation of catchment rainfall.

The remaining phase of the project is to incorporate the developments made into the CSM system and to apply and evaluate the system to estimate design floods in the Thukela catchment. Should this be successful, it is envisaged that the methodology could be used to estimate design floods in other catchments in South Africa.

References

Alexander, W.J.R., 2002. The standard design flood. Journal of the South African Institution of Civil Engineers, 44(1): 26-31.

ASCE, 1997. Flood-Runoff Analysis. ASCE Press, New York, USA. 176 pp.

Boughton, W., 2000. A model for disaggregating daily to hourly rainfall for design flood estimation. Technical Report 00/15. Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Victoria, Australia. 36 pp.

Boughton, W. and Hill, P., 1997. A design flood estimation procedure using data generation and a daily water balance model. Report 97/8. Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Victoria, Australia. 39 pp.

Calver, A., Kay, A.L., Jones, D.W., Kjeldsen, T.R., Reynard, N.S. and Crooks, S., 2004. Flood frequency quantification for ungauged sites using continuous simulation: a UK approach. In: A.E. Rizzoli and A.J. Jakeman (Editors). Complexity and Integrated Resources Management, Transactions of the 2nd Biennial Meeting of the International Environmental Modelling and Software Society. International Environmental Modelling and Software Society. Manno, Switzerland. 5.

Calver, A. and Lamb, R., 1995. Flood frequency estimation using continuous rainfall-runoff modelling. Phys. Chem. Earth, 20(5-6): 479-483.

Calver, A., Lamb, R. and Crewett, J., 2000. Generalised flood frequency estimation using continuous simulation. PIK Report 65. Potsdam Institute for Climate Impact Research, Potsdam, Germany. 412-421 pp.

Calver, A., Lamb, R., Kay, A.L. and Crewett, J., 2001. The continuous simulation method for river flood frequency estimation. CEH Wallingford, UK, Wallingford. 56 pp.

Calver, A., Lamb, R. and Morris, S.E., 1999. River flood frequency estimation using continuous runoff modelling. Paper 11883. Proc. Instn Civ. Engrs Wat., Marit. & Energy. Institution of Engineers, London, UK. 225-234.

Cameron, D.S., Beven, K.J., Tawn, J., Blazkova, S. and Naden, P., 1999. Flood frequency estimation by continuous simulation for a gauged upland catchment (with uncertainty). Journal of Hydrology, 219: 169 - 187.

Cordery, I. and Pilgrim, D.H., 2000. The state of the art of flood prediction. In: D.J. Parker (Editor), Floods. Volume II. Routledge, London, UK. 185-197.

CSIR, 1999. South African National Land Cover (NLC) Database Project. Environmentek, CSIR, Pretoria, South Africa.

Cunge, J.A., 1969. On the subject of a flood propagation computational method (Muskingum method). Journal of Hydraulic Resources, 7: 205-230.

Dunsmore, S.J., Schmidt, E.J. and Schulze, R.E., 1986. Antecedent soil moisture in design runoff volume estimation. WRC Report No. 155/1/86. Water Research Commission, Pretoria, RSA. 110 pp.

Ehret, U., 2002. Rainfall and flood nowcasting in small catchments using weather radar. PhD Thesis, University of Stuttgart, Stuttgart, Germany.

Frezghi, M.S., 2005. The development and assesment of a methodology to improve the estimation of the spatial distribution of rainfall. Draft MSc Eng. Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermartizburg, South Africa.

Gorgens, A.H.M., 2002. Design Flood Hydrology. In: G. Basson (Editor), Design and rehabilitation of dams. Institute for Water and Environmental Engineering, Department of Civil Engineering, University of Stellenbosch, South Africa. 460-524.

Knoesen, D.M., 2005. The Development And Assessment Of Techniques For Daily Rainfall Disaggregation In South Africa. Draft MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermartizburg, South Africa.

Lamb, R., 1999. Calibration of a conceptual rainfall-runoff model for flood frequency estimation by continuous simulation. Water Resources Research, 35: 3103-3114.

Pegram, G.G.S. and Clothier, A.N., 2001a. High resolution space-time modelling of rainfall: the "String of Beads" model. Journal of Hydrology, 241(1-2): 3-25.

Pegram, G.G.S. and Clothier, A.N., 2001b. High resolution space-time modelling of rainfall: the "String of Beads" model. WRC Report No. 752/1/99. Water Research Commission, Pretoria, South Africa.

Pike, A. and Schulze, R.E., 1995. AUTOSOIL Version 3: A soils decision support system for South African soils. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA.

Pilgrim, D.H. and Cordery, I., 1993. Chapter 9: Flood Runoff. In: D.R. Maidment (Editor), Handbook of Hydrology, McGraw-Hill, New York, USA.

Punmia, B.C. and Pande, B.B.L., 1981. Irrigation and Water Power Engineering. Standard Publishers Distributors, Delhi, India.

Rahman, A., Hoang, T.M.T., Weinmann, P.E. and Laurenson, E.M., 1998. Joint probability approaches to design flood estimation: A review. Report 98/8. Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Victoria, Australia. 70 pp.

Reed, D., 1999. Flood Estimation Handbook. Volume 1: Overview. Institute of Hydrology, Wallingford, Oxfordshire, UK. 108 pp.

Schmidt, E.J. and Schulze, R.E., 1984. Improved estimates of peak flow rates using modified SCS lag equations. WRC Report No. 63/1/84. Water Research Commission, Pretoria, RSA. 145 pp.

Schulze, R.E., 1982. Adapting the SCS stormflow equation for application to specific events by soil moisture budgeting. ACRU Report No. 15. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA. 63 pp.

Schulze, R.E., 1995. Hydrology and Agrohydrology : A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Report TT69/95. Water Research Commission, Pretoria, RSA.

Schulze, R.E., 2001. National Land Cover Classification. Development of a Decision Support System for the ACRU model. School of Bioresources Engineering and Environmental Hydrology, University of Natal, Pietermaritzburg, South Africa. 25 pp.

Schulze, R.E. and Arnold, H., 1979. Estimation of volume and rate of runoff in small catchments in South Africa. ACRU Report No. 8. Department of Agricultural Engineering, University of Natal, Pietermaritzburg, RSA. 79 pp.

Sinclair, G.S., 2004. Personal communication. School of Civil Engineering, Surveying and Construction Management, University of KwaZulu-Natal, Durban, South Africa.

SIRI, 1987. Land Type Series. Memoirs on the Agricultural Natural Resources of South Africa. Soil and Irrigation Research Institute, Department of Agriculture and Water Supply, Pretoria, South Africa.

Smithers, J.C. and Caldecott, R.E., 1993. Development and verification of hydrograph routing in a daily simulation model. Water SA, 19(3): 263 - 267.

Smithers, J.C. and Caldecott, R.E., 1995. Chapter 13: Hydrograph routing. In: R.E. Schulze (Editor), Hydrology and Agrohydrology : A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Water Research Commission, Pretoria, RSA. AT13-1 - AT13-16.

Smithers, J.C. and Schulze, R.E., 2001. Design runoff estimation: A review with reference to practices in South Africa. Proceedings of Tenth South Africa National Hydrology Symposium: 26 - 28 September, 2001. School of BEEH, University of Natal. Pietermaritzburg, RSA.

Smithers, J.C. and Schulze, R.E., 2003. Design rainfall and flood estimation in South Africa. WRC Report No. 1060/01/03. Water Research Commission, Pretoria, RSA. 155 pp.

Smithers, J.C., Schulze, R.E. and Kienzle, S.W., 1997. Design flood estimation using a modelling approach. In: D. Rosbjerg, N. Boutayeb, A. Gustard, Z.W. Kundzewicz and P.F. Rasmussen (Editors), Sustainability of Water Resources Under Increasing Uncertainty. IAHS Publication 240. 365 - 376.

Smithers, J.C., Schulze, R.E., Pike, A. and Jewitt, G.P.J., 2001. A hydrological perspective of the February 2000 floods: A case study in the Sabie River catchment. Water SA, 27(3): 325-332.

Steel, M.E., Black, A.R., Werrity, A. and Littlewood, I.G., 1999. Reassessment of flood risk for Scottish rivers using runoff data. In: L. Gottschalk, D. Reed, D. Rosbjerg and J. Olivery (Editors), Hydrological Extremes: Understanding, Predicting, Mitigating. IAHS Publication 255. 209-215.

Tewolde, M.H., 2005. Flood routing in ungauged catchments using Muskingum methods. Draft MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermartizburg, South Africa.

Weddepohl, J.P., 1988. Design rainfall distributions for Southern Africa. Unpublished M.Sc. Dissertation, Department of Agricultural Engineering, University of Natal, Pietermaritzburg, South Africa.